DEVELOPMENT OF TUNABLE K_U-BAND REACTANCE AMPLIFIER

REPORT NO. 1

Signal Corps Contract DA-36-039-sc-90779
Department of the Army Project No. 3A99-21-002

First Quarterly Progress Report

1 July 1962 to 30 September 1962

U. S. Army Signal Research and Development Laboratory
Fort Monmouth, New Jersey

AIRBORNE INSTRUMENTS LABORATORY
A DIVISION OF CUTLER-HAMMER, INC.
Deer Park, Long Island, New York

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OBJECTIVE

The objective of this program is to develop stable, low-noise, tunable K_U-band reactance amplifiers.

Prepared by

J. Whelehan

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I. PURPOSE

A tunable, dual-channel, K_u-band, reactance amplifier system is to be designed, developed, and fabricated under Contract DA 36-039-sc-90779. The specified electrical characteristics of this system are:

Tuning range	15.850 to 16.150 Gc
Noise figure	Less than 4 db when operated at room temperature
Power gain	Greater than 20 db
Bandwidth	30 Mc
Absolute phase stability (between channels)	Less than 1 degree
Absolute gain stability (between channels)	Less than 0.1 db

II. ABSTRACT

The characteristics of the varactor needed for this system were studied in conjunction with the development of a technique for determining the figure of merit of the diode. Various amplifier configurations were considered and the effects of pump power and pump frequency variations on the gain and phase stability of the amplifier were investigated.

III. PUBLICATIONS, LECTURES, REPORTS AND CONFERENCES

A conference was held on 14 September 1962 at the Philco Corporation, Philadelphia, Pennsylvania to ascertain that the electrical and mechanical characteristics of the amplifier system would be compatible with the system to be retrofitted. The conference was attended by the following personnel:

<u>USASRDL</u>

F. Senko

<u>AIL</u>

P. Lombardo

J. Whelehan

<u>PHILCO</u>

A. Meador

IV. FACTUAL DATA

A. OVERALL SYSTEM

A noise figure (F) of less than 4 db (single side-band) at room temperature is specified for the amplifier system. For a one-port nondegenerate amplifier, the minimum noise figure is (reference 1):

$$F \approx 1 + 2r(1 + \sqrt{1 + 1/r}) \tag{1}$$

where

$$r = \left(\frac{f_1}{M}\right)^2,$$

f_1 = signal frequency,

M = diode figure of merit (reference 2).

Assuming a signal frequency of 16 Gc, the minimum achievable noise figure can be determined as a function of the diode figure of merit. To achieve this optimum noise figure, the optimum pump frequency must be used. This is determined by (reference 1):

$$f_{op} = f_1 \sqrt{1 + 1/r} \tag{2}$$

where f_{op} is the optimum pump frequency.

Figure 1 is a plot of the minimum achievable noise figure as a function of the diode figure of merit and the optimum pump frequency needed to achieve this noise figure. From Figure 1, it can be seen that in order to achieve a 4-db noise figure at 16 Gc (assuming no circulator loss), the minimum figure of merit required is 33.5 Gc with a pump frequency

of 36.6 Gc. By taking the circulator losses into account ($\approx$0.5 db), the minimum figure of merit required to achieve a 3.5-db noise figure is 38.5 Gc with a pump frequency of 42 Gc. The maximum figure of merit used in present amplifiers is about 20 Gc. From these considerations, it can readily be seen that the diodes required for this system must have a figure of merit about twice that of the diodes being used at the present time.

The bandwidth specification of 30 Mc with a gain of 20 db corresponds to a voltage gain-bandwidth product of 300 Mc or a fractional gain-bandwidth product of 0.019. The gain-bandwidth product of a one-port nondegenerate amplifier is (reference 3):

$$G^{\frac{1}{2}} B \approx \frac{2B_1}{1 + B_1/B_2} \tag{3}$$

where

B_1 = signal bandwidth,
B_2 = idler bandwidth.

The maximum gain-bandwidth product occurs when the idler bandwidth is equal to the signal bandwidth. Using this criterion for the gain-bandwidth product required, $B_1 = B_2 =$ 300 Mc, which is relatively small. Using the Manley-Rowe criterion for gain-bandwidth product (reference 4):

$$G^{\frac{1}{2}} B \approx \frac{C_1}{C_o} \sqrt{f_1 \; f_2} \tag{4}$$

where

$\frac{C_1}{C_o}$ = nonlinearity ratio,
f_1 = signal frequency,
f_2 = idler frequency.

In the ideal case, assume $C_1/C_0 = 0.2$ (which is relatively small) and $f_2 = 23$ Gc, $G^{1/2} B = 3.84$ Gc. Assuming a 4:1 degradation in gain-bandwidth product caused by extraneous stray capacitances and a narrowing of bandwidth because of the waveguide mounting of the diode, the resultant value of $G^{1/2} B = 960$ Mc. From these calculations, it can be seen that the 30-Mc bandwidth can be satisfactorily achieved.

The amplifier must be able to be tuned between 15.850 and 16.150 Gc. An adjustment provision will be included in the amplifier so that the absolute gain and phase limits will be able to be obtained at any frequency within the tuning range. Tuning is necessary because the frequency of the magnetron will vary somewhat in each replacement magnetron.

The amplifiers can be tuned in two ways--mechanical and electrical. Only general tuning techniques will be considered at this time; specific techniques will be considered as the system design progresses. Mechanical techniques will include capacitance screws, slide-screw tuners, sliding shorts, etc. Although these techniques are very useful for passive devices, they are not well-suited to reactance amplifiers unless special precautions are taken. Since a reactance amplifier is a negative-resistance device, it is very sensitive to tuning element changes. These changes can be caused by temperature variations. Only by using broad-band circuits and special mounting techniques with these tuning elements is it possible to stabilize an amplifier system in amplitude and phase. This type of tuning is considered as a secondary approach.

Electrical tuning is accomplished by changing the bias voltage across the diode. In this technique, the bandwidth of the idler circuit should be much less than that of the signal circuit. Thus, any change in capacitance has a

more pronounced effect on the idler tuning and a very small effect on the signal circuit. As the bias voltage is changed, the idler center frequency changes and, with a fixed pump frequency, the pass band of the signal circuit is traced out; in effect, a tunable amplifier is created. Electrical tuning can also be achieved by varying the pump frequency. In this technique, the idler frequency is fixed and, as the pump frequency is changed, the signal tuning follows. The primary tuning technique for this system should consist of either of the two techniques or a combination of both.

B. DIODES

The minimum figure of merit that the diode must have to achieve a 4-db overall noise figure is 38.5 Gc. As previously mentioned, the maximum figure of merit measured was about 20 Gc. However, this figure was obtained by using a diode that had a relatively low cutoff frequency. Assuming that the nonlinearity of the diode remains constant as the cutoff frequency changes, theoretically the figure of merit can be achieved. Table I lists the diodes that were procured for this program and their characteristics as well as their calculated figures of merit.

Although the calculated figure of merit for some of the gallium-arsenide diodes does not appear to be usable in this application, it should be mentioned that the calculations for Table I were performed at 0-volt bias. The best operation of gallium-arsenide diodes occurs at about -2 volts bias. Under these conditions, the figures of merit of all the diodes are comparable. In addition, the assumed values of C_1/C_0 were determined experimentally in previous programs.

TABLE I

DIODE SPECIFICATIONS

Diode	C_j (pf)	$C_{package}$ (pf)	F_c (Gc)	M (Gc)	$\frac{C_1}{C_o}$
TI A612	0.428	0.27	103.8	26	0.25
TI A612	0.271	0.27	93.2	25	0.25
MA 4551	0.50	0.20	98	39.2	0.40
MS 4106	0.51	0.18	130	32.5	0.25
MS 4106	0.40	0.18	130	32.5	0.25
S 103	0.20	0.036	162	40.6	0.25

where C_j = junction capacitance at 0-volt bias,
F_c = diode cutoff frequency at 0-volt bias,
M = diode figure of merit.

Manufacturer Designation

TI - Texas Instruments
MA - Microwave Associates
MS - Microstate
S - Solrac

As can be seen from Table I, both silicon and gallium-arsenide diodes are being considered. Gallium-arsenide varactors are being considered because the bandwidth of the amplifier is not a large fractional bandwidth.

However, the figure of merit is not the only consideration that a diode must satisfy to be effective at the specified frequencies. Since the signal frequency of the amplifier is 16 Gc, a waveguide structure will be used for all frequencies of interest. The circuit properties of the diode in the waveguide will have to be determined. The characteristics of a diode when placed across a waveguide structure can vary considerably from diode to diode.

The losses of the diode must also be determined. When placed across a waveguide, the losses in the junction material are not the only losses that occur. The supporting posts on either side of the varactor junction also contribute to the overall loss. Since a large buildup is required in the electric field at the junction, this field will produce large surface currents in the supporting posts of the diode. Depending on the nature of the material and the ratio of the diameter of the post to the "a" dimension of the waveguide, these losses will vary from diode to diode. In addition, the losses caused by the ceramic portion of the diode will have to be considered. All these factors tend to decrease the cutoff frequency of the diode, thereby reducing the figure of merit.

Furthermore, the form factor of the diode affects amplifier performance substantially. This factor determines the impedance of the diode across the waveguide. This impedance is a major factor in amplifier performance. If the supporting posts of the diode are substantial obstacles, this impedance is equivalent to a large shunt inductance across the diode, which would in effect short out the diode. Other limiting factors are at present being determined.

The characteristics of various diodes when placed across a K_u-band waveguide are being measured. They will be tested at both 0-volt bias and the +1 μa point. From these measurements, the effective admittance of the diode can be determined. Also, the effective nonlinearity can be determined and from this the suitability of the diode for this particular application.

After these measurements are completed, it still will be necessary to determine which diode will give the required figure of merit. The figure of merit can easily be determined by converting the test jig for the diodes into a degenerate amplifier. The operation of this type of amplifier is relatively simple, and the figure of merit for each diode can then be determined.

Using the static admittance tests and the operation of the diodes in a degenerate amplifier, the best diode will be chosen for the amplifier.

C. AMPLIFIER CONFIGURATION

Since the nondegenerate parametric amplifier is a three-frequency device, the most difficult design problem is the independent tuning adjustments at the signal, idler, and pump frequencies. In addition, to achieve the maximum voltage gain-bandwidth product, it is necessary that both the signal and idler frequencies be tuned by reactive elements that are as independent of frequency as possible. Since lumped constants are not practical at K_u-band, resonators operating in the first quarter mode must be used. Furthermore, the diode must be mounted in a configuration that minimizes the stray parasitic reactances associated with the diode.

Previous experience has indicated that a minimum of diode parasitic reactances is associated with TEM transmission lines. However, at a center signal frequency of 16 Gc, wave-

guide transmission lines must be used. The separation of signal and idler circuits can be accomplished in either a single-ended or double-ended mount.

In a single-ended mount only one diode is used. The required separation between the signal and idler frequencies can be accomplished by either of two means. One method, which appears simple and actually is not, is to use some sort of filter. Problems arise because tuning can no longer occur at the first appropriate quarter mode. This makes the tuning critical and the amplifier inherently unstable. This technique will be investigated, but will not be used for the first approach.

The other technique, used in a single-ended amplifier, establishes the signal and idler cavities in such a way that the propagating waves at these two frequencies are orthogonal to one another. This can be accomplished by using either a surface-wave propagation or a form of dielectric waveguide; both means of propagation are presently under consideration.

The double-ended configuration is an extension of the balanced amplifier into a waveguide configuration (reference 2). In this configuration, the separation of signal and idler frequencies is based on a null point at the junction of the two diodes at the idler frequency even though the self-resonant frequency of the diode is lower than the idler frequency. This configuration could be readily used for this particular application and is also under consideration.

D. AMPLITUDE AND PHASE STABILITY

1. SINGLE AMPLIFIER

A reactance amplifier is basically a reflection-type amplifier in which the output power is $|\Gamma|^2$ times the input power, where $|\Gamma|$ is the reflection coefficient of the device. The defining characteristics of the amplifier are

$|\Gamma|e^{j\phi}$, where $|\Gamma|$ is the gain and ϕ is the phase angle associated with the device. Presented mathematically,

$$|\Gamma|e^{j\phi} = \frac{Z_{in} - Z_g}{Z_{in} + Z_g} \tag{5}$$

where

Z_{in} = input impedance of the device,
Z_g = generator impedance.

Using reference 3, the input impedance of the amplifier is:

$$Z_{in} = R_D\left\{\left[1 - \frac{\frac{M^2}{f_1 f_2}}{1 + \left(2Q_2 \frac{\Delta f_2}{f_2}\right)^2}\right] + j\left[2Q_1 \frac{\Delta f_1}{f_1} - \frac{2Q_2 \frac{M^2}{f_1 f_2} \frac{\Delta f_2}{f_2}}{1 + \left(2Q_2 \frac{\Delta f_2}{f_2}\right)^2}\right]\right\} \tag{6}$$

where

$M = (C_1/C_o)f_c$ = diode figure of merit,
R_D = diode series resistance,
Subscript 1 is associated with the signal frequency,
Subscript 2 is associated with the idler frequency.

At resonance $\Delta f_1 = \Delta f_2 = 0$, and the input impedance is a pure negative resistance. Thus,

$$Z_{in} = R_D\left[1 - \frac{M^2}{f_1 f_2}\right] \quad \frac{M^2}{f_1 f_2} >> 1 \tag{7}$$

As can be seen from equation 6, the gain stability is determined solely by the stability of M, which, in turn, depends on the stability of the pump power. From previous

experiments, a 0.1-db change in pump power results in a 1.0-db change in amplifier gain. Since the relative gain stability must be less than 0.1 db, the stability of the pump power has to be controlled to less than 0.1 db. This could mean that the forward pump power may have to be controlled by a feedback loop.

As can be seen from equation 1, the phase stability of the reactance amplifier, which is related to the input impedance, is also dependent upon the stability of M. It also depends upon the frequency stability of the klystron. The 3-db bandwidth corresponds to the ± 45 degree phase points. By assuming a 30-Mc wide amplifier, as indicated in the specifications, the slope of the phase characteristics is 3 deg/Mc. After subtracting the phase characteristic caused by the signal circuit, to hold to the relative phase stability of less than 1 degree, the frequency stability of the klystron must be better than 2 Mc for an idler bandwidth of 300 Mc. As the idler bandwidth is increased, this dependence of pump frequency stability will improve. Thus, the operation of the klystron would not have to be in a temperature-controlled environment.

2. DOUBLE AMPLIFIERS

To achieve the relative gain and phase stability and to facilitate tuning, it is almost mandatory that a common pump source be used. Furthermore, the external circuits associated with the amplifier must have the same phase shift. This will require a careful investigation of the components of each amplifier.

V. CONCLUSIONS

Electrical tuning of the amplifier appears to be the most practical technique from the viewpoint of system reliability and complexity. This method of tuning may be able to be used to remotely tune the amplifiers--a distinct advantage.

The forward pump power of the klystron may have to be controlled to better than 0.1 db to achieve the gain and phase stability required. However, control of the pump frequency does not seem to be as critical and will only have to be stable to about 2 Mc in the worst case.

VI. PROGRAM FOR NEXT INTERVAL

During the next interval, the diodes will be completely evaluated in a waveguide mount at 16 Gc. When this has been accomplished, the diode test jig will be converted into a degenerate amplifier for a determination of the diode figure of merit. From these measurements, the best diode will be chosen and the design and construction of the K_u-band amplifier will begin.

VII. IDENTIFICATION OF PERSONNEL AND CONTRACT EFFORT

Of the total funds allotted for this contract, about 12 percent have been expended. The progress of the work is satisfactory, and the program can be completed within the allotted funds and on schedule. A list of key personnel assigned to this contract, their biographies, and the total number of hours spent by each during the past quarter follows:

	Hours
P. P. Lombardo	180
J. J. Whelehan	251
I. Haber	76
E. Moley	232

PETER P. LOMBARDO

Mr. Lombardo received a B.E.E. degree from the Polytechnic Institute of Brooklyn in 1953. He is presently taking graduate courses at the same college.

In June 1953, Mr. Lombardo joined AIL, where he participated in the design of the Airport Surface Detection Equipment (ASDE) Radar. He has also been engaged in the design and development of UHF and microwave receivers, low-noise vacuum-tube amplifiers, and parametric amplifiers for use in communication and radar systems. He has made theoretical and experimental investigations on broad-band amplifier coupling networks in the VHF, UHF, and microwave regions, has been concerned with the design of amplifier input networks to obtain low noise figures over broad bandwidths, and has made fundamental contributions to the design of traveling-wave, backward-wave, and cavity-type parametric amplifiers. In addition, Mr. Lombardo has worked on the development of microwave harmonic and subharmonic generators using varactor diodes as the essential nonlinear element, has performed extensive theoretical and experimental work on the development of accurate, broad-band, temperature-limited diode noise sources, and has a wide range of experience in designing various types of IF amplifiers.

Mr. Lombardo is currently functioning as a Consultant/Group Leader in providing technical direction to a large number of parametric amplifier programs, including the ground station receivers for the Advent Communications Satellite Program and the Syncom Communications Satellite Program. These programs are systems requiring extensive parametric amplifier, circulator, varactor multiplier, and limiter programs.

Mr. Lombardo is a member of Tau Beta Pi and Eta Kappa Nu.

JAMES J. WHELEHAN

Mr. Whelehan received a B.E.E. degree in 1959 from the Polytechnic Institute of Brooklyn. He is presently taking graduate courses at the same college.

In June 1959, Mr. Whelehan joined AIL as an engineer in the Department of Applied Electronics, where he has been concerned with the development of low-noise wide-band solid-state amplifiers. He has done theoretical and experimental investigations on broad-band amplifiers in the microwave region.

Mr. Whelehan is presently working on the development of UHF and C-band parametric and tunnel-diode amplifiers, and has produced units with gain-bandwidth products in excess of 1500 Mc.

IRVING HABER

Mr. Haber received a B.E.E. degree in 1961 from the Cooper Union. He is currently taking graduate courses at the Polytechnic Institute of Brooklyn.

In June 1961, Mr. Haber joined AIL as an engineer in the Department of Applied Electronics where he has been concerned with the development of low-noise wide-band parametric amplifiers.

EDMUND W. MOLEY

Mr. Moley received a B.E.E. degree in 1960 from the Polytechnic Institute of Brooklyn. From September 1960 to September 1961, he attended the Polytechnic Institute Graduate School full-time as a Junior Research Fellow. During this time, he investigated high-frequency breakdown phenomena at the Microwave Research Institute. He has completed the course requirements for his M.E.E. degree, and is presently continuing graduate studies at the same college.

In September 1961, Mr. Moley joined AIL as an engineer in the Department of Applied Electronics where he participated in the development of nonreciprocal ferrite devices. Mr. Moley is presently working on the development of low-noise K_u-band reactance amplifiers.

Mr. Moley is a member of Tau Beta Pi and Eta Kappa Nu.

VIII. REFERENCES

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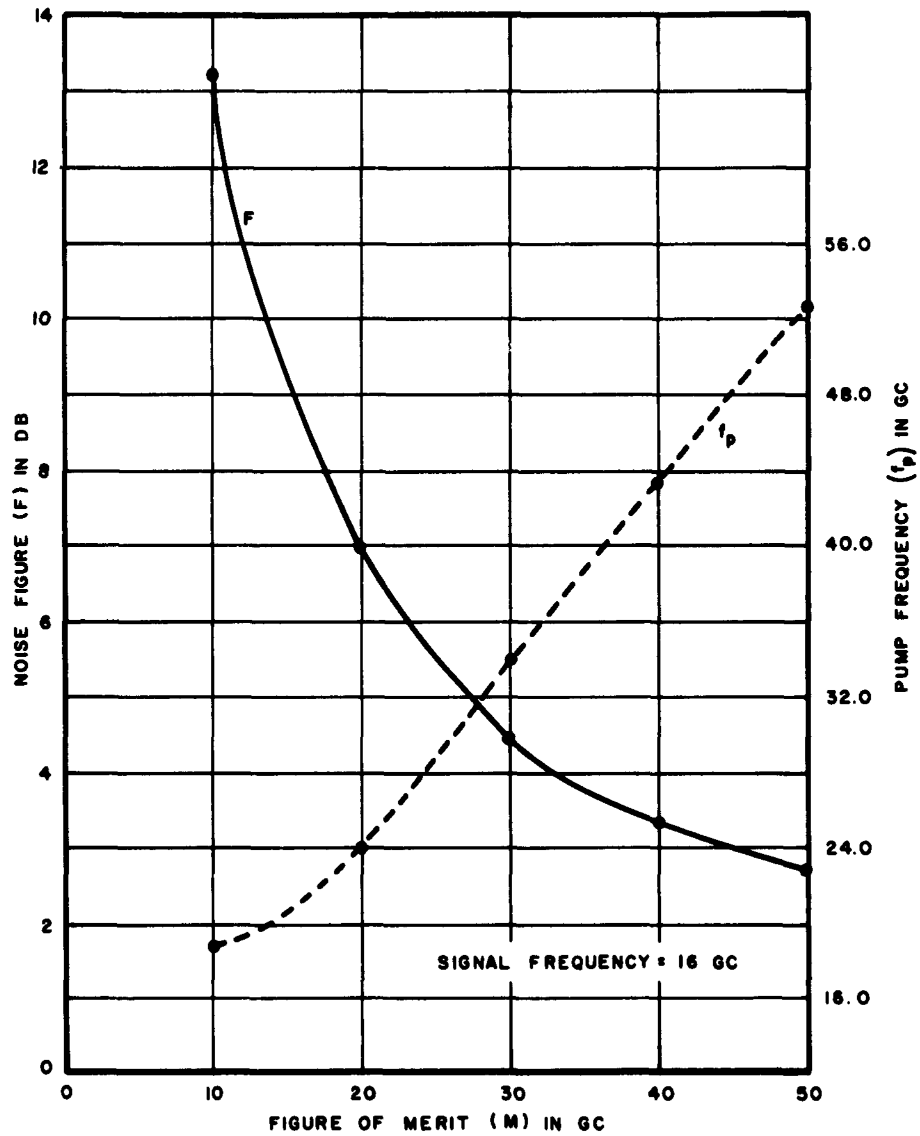

FIGURE 1. MINIMUM NOISE FIGURE WITH OPTIMUM PUMP FREQUENCY VS DIODE FIGURE OF MERIT

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